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Does Processing Speed Mediate the Effect of Pediatric Traumatic Brain Injury on Working Memory?

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Abstract

Objective—Processing speed (PS) and working memory (WM), core abilities that support learning, are vulnerable to disruption following traumatic brain injury (TBI). Developmental increases in WM are related to age-related changes in PS. The purpose of this study was to investigate whether WM deficits in children with TBI are mediated by PS.

Method—The performance of children with complicated-mild, moderate, and severe TBI (n=77) was examined relative to an orthopedic injury (n=30) and a healthy comparison group (n=40) an average of 4 years after injury (range 8 months to 12 years). Coding was utilized as a measure of PS, while the WM measures included complex verbal and visual-spatial span tasks with parallel processing requirements. Mediation analysis examined whether TBI might have an indirect effect on WM through PS.

Results—Children in the TBI group performed more poorly than the combined comparison groups on Coding and visual-spatial WM. Verbal WM scores were lower in TBI and the healthy comparison relative to the orthopedic group. TBI severity group differences were found on Coding, but not WM measures. The relation between Coding and both the WM tasks was similar. Bootstrap regression analyses suggested that PS, as measured by Coding, might partially mediate the effect of group performance on WM.

Conclusions—TBI disrupts core PS and WM abilities that scaffold more complex abilities. Importantly, slowed PS was associated with WM deficits commonly identified following pediatric TBI. Implications of our findings regarding the relation between PS and WM may suggest interventions for children and adolescents following TBI.

Keywords

traumatic brain injury; working memory; processing speed; outcome; mediation model

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Pediatric traumatic brain injury (TBI) accounts for approximately 30% of injuries among children, and is a leading cause of long-term disability (Langlois, Rutland-Brown, & Thomas, 2004). Moderate to severe TBI is often associated with diffuse, multifocal neuronal injury caused by both the initial damage at the time of injury and numerous secondary factors, including hypoxic-ischemia, excitotoxic cascades of neurotransmitters, and inflammatory processes (Povlishock & Katz, 2005; Masel & DeWitt, 2010). In children and adolescents, this diffuse brain injury is often associated with widespread deficits in numerous cognitive domains, including general cognitive functioning, declarative and working memory, attention, processing speed, visual spatial skills, fluency, and problem solving (Allen et al., 2010; Anderson, Catroppa, Godfrey, & Rosenfeld, 2012; Babikian & Asarnow, 2009; Catroppa, Anderson, Godfrey, & Rosenfeld, 2011; Yeates, 2010). At present, it is unclear whether TBI directly disrupts complex abilities, such as academic skills, or whether TBI disrupts core abilities, such as working memory and processing speed, that scaffold more complex abilities such as mathematical reasoning or reading comprehension (Ewing-Cobbs et al., 2004). The purpose of the present study was to characterize the impact of TBI on both processing speed and working memory and to examine whether deficits in working memory may be attributed in part to slowed processing speed.

Development of Processing Speed and Working Memory

Processing speed (PS) and working memory (WM) are core abilities that support learning (Gathercole, Alloway, Willis, & Adams, 2006; Espy et al., 2004). The construct of PS incorporates both the efficiency of analyzing perceptual inputs and efficiency of responding. Shanahan et al. (2006) provided a working definition of PS, which reflects cognitive efficiency involved in integrating lower level perceptual stimuli, higher level cognitive information, and output speed. Although PS is often viewed as a unitary construct, PS is divisible into two distinct factors including simple/choice RT and speed of performing complex tasks such as serial addition that require mental manipulation (Chiaravalloti, Christodoulou, Demaree, & DeLuca, 2003). Convergent validity analyses of tasks included in the recent NIH Toolbox effort to develop and validate PS measures revealed that a composite score including both simple and complex RT measures was slightly more strongly related than any test in isolation to the “gold standard” PS factor score from the Wechsler scales (Carlozzi, Tulsky, Kail, & Beaumont, 2013).

WM has been defined as the mental workspace in which information relevant to a given task is monitored, processed, and maintained to allow responding to immediate demands of the environment (Baddeley & Logie, 1999). Other theories of WM purport that it is comprised of the ability to focus attention on relevant stimuli, while ignoring, or inhibiting irrelevant stimuli (Engle, 2002). Deficits in PS and/or WM have been related to a wide range of cognitive and academic difficulties in children with developmental and acquired disorders, including reading disability, math disability, attention-deficit/hyperactivity disorder, preterm birth, and acute lymphoblastic leukemia (Schatz, Kramer, Ablin, & Matthay, 2000; Christopher et al., 2012; Jacobson et al., 2011; Mulder, Pitchford, & Marlow, 2011; Shanahan et al., 2006).

Childhood is a critical time for both PS and WM development (Diamond, 2002; Gathercole, Pickering, Ambridge, & Wearing, 2004; Kail, 1991). Efficiency in each area improves from childhood through adolescence. The nonlinear relation between memory span and age parallels the nonlinear increase in PS over the same developmental period, suggesting a similar developmental pattern of each domain (Fry & Hale, 2000). Furthermore, WM development may be related to improvements in PS. Using a counting span task, Case, Kurland, and Goldberg (1982) asked children of various ages to count dots and to later recall the number of dots of a specific color. Recall ability was related to the speed at which children counted. More efficient, faster counting placed fewer demands on WM, thus allowing for a greater availability of recall resources in WM, which was also suggested by Baddeley (1986).

Developmental increases in verbal memory span can be attributed to increased articulation rates, which are determined by developmental improvements in PS (Chuah & Maybery, 1999; Hulme, Thomson, Muir, & Lawrence, 1984; Kail & Park, 1994). Chuah and Maybery (1999) also found that this relation extended to spatial memory span and concluded that PS is related to both verbal and spatial memory spans. Thus, it has been found that memory span can be predicted from the rate at which children process and covertly rehearse verbal and visual information.

While the aforementioned studies have considered the relation between PS and WM using regression analyses, Fry and Hale (1996) performed path analyses to assess relations among age, speed, and WM in 214 typically-developing children between second and seventh grade, high school seniors and first and second year college students. The authors reported that 71% of the total age-related effect on WM capacity was mediated by age-related changes in PS. The individual differences in PS continued to affect WM capacity, even after controlling for age. Fry and Hale (1996) concluded that most developmental increases in WM were mediated by age-related changes in PS. The findings of this study confirm that PS and WM are strongly related in children, and exhibit similar developmental patterns.

Processing Speed and Working Memory in Children with TBI

PS and WM are particularly vulnerable to disruption following pediatric TBI, with more severe injuries producing more pronounced deficits (Bawden, Knights, & Winogron, 1985; Conklin, Salorio, & Slomine, 2008; Ewing-Cobbs et al., 1998; Ewing-Cobbs et al., 2008; Levin et al., 2002; Levin et al., 2004; Roncadin, Guger, Archibald, Barnes, & Dennis, 2004; Taylor et al., 1999; Thompson et al., 1994; Wilde et al., 2006; Winogron, Knights, & Bawden, 1984). However, with regard to WM, most studies investigating the effects of TBI on WM focus primarily on verbal WM, with relatively few studies investigating the effects of TBI on visual WM or on different domains purported to comprise WM such as central executive processes or inhibition (but see Gorman, Barnes, Prasad, Swank, & Ewing-Cobbs, 2012). Additionally, it is not well understood whether deficits in WM following TBI may be mediated by another cognitive process. That is, it has not been investigated whether deficits in PS resulting from TBI in childhood might underlie deficits in WM.

Rationale and Hypotheses

Investigating the relation between PS and WM in children would be of interest because both cognitive domains are still developing during childhood, and TBI could impede the normal developmental trajectory of these domains. Identifying core abilities impacted by TBI may also suggest specific intervention strategies for remediation of cognitive deficits.

The present study examined PS and WM performance in children in the post-acute period following TBI relative to an orthopedic comparison group and a healthy comparison group. Consistent with previous literature, we hypothesized that the TBI group would perform more poorly than both comparison groups on PS and WM measures. Given that previous studies have found similar relations between speed of rehearsal and both verbal and spatial memory spans in typically developing children, we hypothesized that the relation between PS and WM would be similar for both verbal and visual-spatial WM. Lastly, given that it has been shown (albeit not using mediation model analysis) that there is a relation between PS and WM in typically developing children and that both domains exhibit similar developmental patterns, we hypothesized that PS would at least partially mediate the influence of TBI on WM.

Method

Participants

This study combined two prospective longitudinal studies examining neuropsychological outcomes after pediatric injury in young children and in school-aged children and adolescents. The initial cohort was injured and enrolled in previous projects between 1994 and 1998 and the second cohort was injured between 2004 and 2007. With the exception of age at injury, recruitment procedures and inclusion criteria were the same across cohorts. Outcomes were assessed in each cohort using similar procedures and age-appropriate measures. In the current study, participants included 77 children who sustained TBI, 30 children with orthopedic injuries not involving the skull or face and 40 healthy comparison children. Children in the TBI group were recruited from the Level 1 Pediatric Trauma Center at Children's Memorial Hermann Hospital in Houston, Texas. These children were injured between the ages of 2 months and 16 years and evaluated between 8 months and 12 years post injury. Age at test ranged from 6 years to 18 years with a mean of 13.2 (sd = 3.24) years. The severity of TBI was categorized based on the lowest post-resuscitation Glasgow Coma Scale (GCS) score (Teasdale & Jennett, 1974) and acute neuroimaging findings. Complicated-mild TBI was defined by GCS scores from 13-15 and neuroimaging evidence of extra-axial hemorrhage or parenchymal injury (n=7). Moderate (n=16) and severe (n=54) TBI had GCS scores of 9-12 and 3-8, respectively, with or without positive neuroimaging findings. Inclusionary criteria for children in the TBI group were: 1) TBI resulting from acceleration-deceleration or blunt impact injuries caused by vehicular accidents, falls or impact with a blunt object, 2) complicated-mild, moderate, or severe TBI, 3) skeletal or body Abbreviated Injury Scale (Baker, O'Neill, Haddon, & Long, 1974) scores ≤ 2 in children with complicated mild or moderate TBI to minimize any confounding influence of severe orthopedic injury on accurate assessment of GCS scores and outcome, and 4) bilingual or primarily English-speaking.

Exclusionary criteria for the TBI group were: 1) children with injury mechanisms occurring with low frequency that have differing outcomes than acceleration/deceleration injuries (e.g. penetrating brain injuries), 2) history of prior medically attended TBI, 3) children of illegal immigrants and families residing outside the catchment area due to difficulty maintaining enrollment, and 4) children with major pre-injury neurodevelopmental or psychiatric disorders that would interfere with the assessment of the impact of TBI on outcomes. (e.g., intellectual disability, moderate to severe autism spectrum disorder) Exclusionary criteria were determined with a brief questionnaire administered to parents. Exclusionary criteria 2-4 were also applied to the comparison groups.

The orthopedic comparison group was composed of 30 children who sustained orthopedic injuries not involving the head or face. Children in the orthopedic group were recruited from the same Level 1 Pediatric Trauma Center between 2004 and 2007. Prior to recruitment, the medical record was screened to ensure that children with orthopedic injuries did not have evidence of head injury, such as bruising or abrasions on the head suggesting impact, and did not exhibit alteration of consciousness or symptoms of concussion. Children with orthopedic injuries were enrolled during the acute stage of recovery and were followed longitudinally for 2 years after injury. Data from their 2-year follow-up was selected to provide the best match with age of the TBI group. A second comparison group was composed of 40 healthy children from the community without head or orthopedic injuries. Healthy comparison children were recruited via fliers posted at libraries in the community and well-child programs at the University of Texas Medical School at Houston. Demographic information and descriptive statistics for the TBI and the two comparison groups are presented in Table 1.

Measures

Coding—The Coding subtest of the age-appropriate Wechsler Intelligence was administered to assess processing speed (Wechsler, 1991; 1997). The participant was asked to copy symbols that were paired with simple geometric shapes or numbers in 120 seconds. The total number correctly completed was used in analyses.

Category Listening Span Dual-Task—The Category Listening Span Dual-Task measures verbal WM and includes a dual-task component (Daneman & Carpenter, 1980; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). This task includes five sets of one, two, three, four, or five strings of three words with the number of word strings corresponding to a particular WM span. The participant is asked to tap the table if the string of three words contains an animal name (dual-task component). The child must also remember the last word in each string at the end of the trial. In a two span trial, the examiner might say “apple, dog, door,” then pause for 1 second to allow the participant the opportunity to tap, then say the next word string, “pan, gate, arm.” A correctly performed trial at a span of two would include a tap after the first string, and recall of the words “door” and “arm” in that order. A ceiling was established when the child missed two or more trials at a given level. A basal was established as the lowest level at which three of four trials were correct. Total correct was determined as the total number of trials the participant correctly completed, including those trials below the participant's basal level. There were 20 total trials for this task.

Visuospatial Span Dual-Task—The Visuospatial Span Dual-Task measures visual-spatial WM (Cornoldi et al., 2001) and was created with the same processing demands as the verbal WM measure, allowing for direct comparison of verbal and visual-spatial WM. In the visual-spatial WM measure, the experimenter touches three contiguous positions in a four by four matrix of small square blocks. The child is asked to tap the table if the positions are in a linear pattern and must remember the last location touched in each string by pointing to these blocks at the end of each trial. The task is composed of five sets of one, two, three, four or five string series or memory spans. The same basal and ceiling rules were applied to both tasks. Total correct was also determined as the number of trials (maximum of 20) that the participant successfully completed, including the trials below the basal level.

Procedure

Informed written consent was obtained from the child's guardian. Oral assent was obtained from children ages 6 to 7 years, and written consent was obtained from children 8 years and older, in accordance with guidelines established by the Institutional Review Board at the University of Texas Health Sciences Center at Houston. Participants were examined individually in an outpatient setting at the University of Texas Health Sciences Center at Houston, in a quiet testing room. Evaluation was conducted by a trained research assistant. Children were given a large battery assessing cognitive and academic abilities, following standardized procedures. The testing time was approximately 45 minutes for the measures used in the present study and 4 hours for the total battery.

Statistical Analyses

To test the effect of TBI on PS, a 3 group (TBI vs. Orthopedic Comparison vs. Healthy Comparison) univariate analysis of covariance (ANCOVA) was performed in SAS, to determine whether there was a significant performance difference between the groups on Coding. Two contrasts were performed. The first contrast compared the TBI group to a combined comparison group (composed of both the orthopedic group and the healthy group) and a second contrast compared the orthopedic and healthy comparison groups. Age at test was covaried. To determine whether the TBI group performed more poorly than the comparison groups on verbal and visual-spatial measures of WM and to determine whether the group differences depended on the two measures of WM, a 3 group (TBI vs. Orthopedic vs. Healthy comparison) by WM task univariate repeated measures ANCOVA (covarying for age at test) was done for the two WM measures, with planned contrasts comparing the TBI group to the two comparison groups combined and then, comparing the orthopedic and healthy comparison groups.

In the mediation models, the hypothesized causal effect of group membership (TBI, orthopedic, or healthy comparison) on WM was apportioned into its indirect effect on WM through PS and its direct effect on WM (Preacher & Hayes, 2008). Two dichotomous indicators were used to code group, one comparing TBI to the orthopedic group and one comparing TBI to the healthy group. Other contrasts were possible but we were specifically interested in the mediation of differences between the TBI group and the control groups, not the difference between controls. Because there was some indication that there were differential effects of group on the two measures of WM, we examined each WM measure separately. In order to test the significance of each path, a bootstrap regression analysis was performed using the SAS procedure GLM. In this model, the two dichotomous indicators of group were the independent variables, PS was the mediator and each measure of WM was the dependent variable. Age at test was controlled. Five thousand bootstrap samples with replacement were completed for each model. A significant value of the indirect path would support the hypothesis that PS mediates the effect of TBI on WM. Significance was tested using confidence intervals. To determine whether the relation between PS and WM was similar for both verbal and visual-spatial WM, we compared the difference between the parameters for PS and WM variables from the bootstrap analysis. A 95% confidence interval that includes zero would suggest that the relations did not differ.

Results

Demographic and Injury Variables

Demographic variables were examined in the TBI and two comparison groups. Chi-square revealed that the three groups did not differ significantly on ethnicity or sex. Analysis of variance resulted in a significant group difference in maternal years of education. Tukey's HSD comparisons indicated that mothers of children in the TBI group had significantly lower education than mothers of healthy comparison children ($p < .01$) but no other significant group differences were found. To determine whether maternal education needed to be covaried, a partial correlation (covarying age at testing) was run to see if maternal education correlated with any of the outcome measures. None of the correlations was significant (Coding $r_p = 0.06$, $p = .49$, verbal WM $r_p = 0.08$, $p = .37$, visual-spatial MW $r_p = 0.02$, $p = .82$) and so maternal education was not covaried. The age at testing group difference was not significant, but was covaried in subsequent analyses because raw test scores were utilized and were thus not age corrected. IQ was determined using the two-subtest Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999) and there was a significant group difference. Tukey's HSD comparisons indicated that children in the TBI group had significantly lower IQ than children in the orthopedic group and healthy comparison children (both $p < .01$), while the two comparison groups did not differ significantly. Lower IQ in children with TBI is commonly found in the pediatric TBI literature (Jaffe et al., 1992). Injury-related variables for the TBI group are presented in Table 2. “Days to follow commands” was determined as the number of days the GCS motor scale score was below 6.

Given the wide range in age at injury in the TBI sample, partial correlations were run (controlling for age at testing) between this variable and the outcome measures. These correlations were non-significant (Coding $r_p = 0.06$, $p = .64$, verbal MW $r_p = 0.09$, $p = .48$, visual-spatial WM $r_p = 0.22$, $p = .08$) suggesting that age at injury was not significantly related to performance on the measures when controlling for age at testing. Given the wide range in time since injury in the TBI sample, partial correlations were also run (again controlling for age at testing) between this variable and the three outcome measures. Correlations were non-significant for Coding ($r_p = -0.002$, $p = .99$) and verbal WM ($r_p = -0.024$, $p = .84$) but was significant for visual-spatial WM ($r_p = -0.24$, $p = .04$). This suggests that longer time since injury was associated with worse performance on the visual-spatial WM measure only.

Processing Speed and Working Memory Group Comparisons

All three outcome measures were significantly correlated at the .01 significance level, when accounting for age at testing (Coding with verbal WM $r_p = 0.43$, $p < .01$, coding with visual-spatial WM $r_p = 0.47$, $p < .01$, verbal WM with visual-spatial WM $r_p = 0.59$, $p < .01$).

Processing speed—Planned comparisons between the three groups on PS indicated that there was a significant difference between the TBI group and the combined comparison group, $F(1, 129) = 12.81$, $p < .01$, but the difference between the two comparison groups was non-significant $F(1, 129) = 0.16$, $p = .69$. This suggests that the difference between the TBI group and each of the comparison groups is similar. See Table 3a for least squares means and root mean square error. R-squared estimates of effect sizes are also reported, with a value of 0.02 reflecting a small effect size, 0.10 reflecting a moderate effect size and 0.25 reflecting a large effect size (per Cohen interpretations of R-square effect size).

Within the TBI group, we also investigated whether there were injury severity differences on Coding performance, while covarying age at testing. Given literature that suggests that complicated mild and moderate TBI groups have similar outcomes, we combined these two groups (also given the small complicated mild sample size). The effect of severity group on Coding was significant $F(1, 64) = 6.14$, $p = .02$, with the severe group completing fewer items. See Table 3b for least squares means and root mean square error.

Working memory—For the verbal WM measure, contrasts were significant for both the TBI versus combined comparison group analysis $F(1, 143) = 5.91$, $p = .02$ and for the orthopedic versus healthy comparison group analysis $F(1, 143) = 5.45$, $p = .02$. Follow-up tests showed that the orthopedic control differed significantly from both the healthy controls ($p = 0.02$) and the TBI group ($p < 0.01$) whereas the healthy controls and the TBI group did not differ ($p = 0.52$). For the visual-spatial WM task, contrasts were significant for the TBI versus combined group analysis $F(1, 143) = 16.61$, $p < .01$ but not for the orthopedic versus healthy comparison group analysis $F(1, 143) = 0.44$, $p = .51$. Thus, group differences on the verbal WM measure were not the same as group differences on the visual-spatial WM measure. Results of the within measure difference for the contrasts indicated that the difference between visual-spatial and verbal working memory between the orthopedic and healthy comparison groups did not quite reach significance $F(1, 143) = 3.41$, $p = 0.07$. See Table 3a for least squares means and root mean square errors.

We also investigated whether severity of TBI influenced WM measures. There was no significant severity group effect on the verbal WM measure $F(1, 74) = .03$, $p = .86$, or the visual-spatial WM measure $F(1, 74) = 2.43$, $p =.12$. Least squares means and root mean square errors for verbal and visual-spatial WM scores are presented in Table 3b.

Processing Speed as Mediator between Group and Working Memory

Three models were run for each mediation. The first model determined the relation of group (TBI versus orthopedic comparison and TBI versus healthy comparison) to PS, covarying age at testing. Both of the contrasts (TBI vs. Orthopedic and TBI vs. Healthy) were significantly related to Coding (both p's ≤ .01). The second model compared the effect of the same contrasts on each WM measure, controlling for age at testing. The third model compared the effect of the same contrasts on each WM measure, controlling for age at testing and Coding. For verbal WM, the contrast (without Coding) assessing the total effect was significant for the TBI versus Orthopedic group (Total Effect = 2.69, $p < 0.01$) but not for the TBI versus healthy comparison group (Total Effect = 0.83, $p = 0.31$). After adding Coding to each model, the TBI versus Orthopedic contrast was still significant (Direct Effect = 1.99) but the parameter was reduced in size, and the Coding effect was also significant. The TBI versus healthy comparison contrast was not significant (Direct Effect = 0.02) but there was a substantial reduction in the parameter estimate (from 0.783 to −0.008).

For visual-spatial WM, each contrast (without Coding) evaluating the total effect of group was significant (TBI versus Orthopedic Total Effect = 2.71; TBI versus Healthy Total Effect = 2.71; both $p < 0.01$). After adding Coding to the models, both contrasts were significant (TBI versus Orthopedic Direct Effect = 2.00; TBI versus Healthy Direct Effect = 1.70) but with reduced parameters, and Coding was significant as well. Because the direct and indirect effects were significant, these results suggest possible partial mediation.

To test the significance of the partial mediation, the results of the confidence intervals (based on 5000 such bootstrap samples) were examined. The indirect effects for each WM measure had 99% confidence intervals that did not contain zero, equivalent to a two-tailed hypothesis test at the .01 level (see Table 4). This suggests that PS (as measured by Coding) could partially mediate the relation between WM and TBI and each comparison group.

Lastly, to determine whether the relation between PS and the two WM measures were similar, we estimated the difference between the two parameters using a confidence interval for the 5000 estimates. The 95% confidence interval included zero (from −0.041707 to 0.043998), suggesting that the relations did not differ significantly.

Discussion

Processing speed is a core cognitive ability that supports other cognitive abilities, including WM. Slowed PS is a core characteristic of a number of developmental and acquired disorders of childhood (Jacobson et al., 2011; Mulder et al., 2011; Palmer et al., 2013; Shanahan et al., 2006) and has been implicated as a prominent deficit area following moderate to severe TBI (Babikian & Asarnow, 2009). The aims of the present study were to characterize PS and WM deficits in children following TBI. In particular, we examined the relation between PS as measured by Coding and both verbal and visual-spatial modalities of WM, and whether PS might mediate the relation between TBI and WM deficits. Relative to the combined orthopedic and healthy comparison group, the TBI group had lower Coding scores and shorter verbal and visual-spatial spans on complex WM tasks. The group differences on both verbal and visual-spatial WM tasks suggest difficulties with the central executive or similar domain-general resources that support complex cognition, rather than with modality-specific storage or manipulation of information in WM. In addition, the relation between PS (as measured by Coding) was similar for both verbal and visual-spatial measures of WM. Lastly, bootstrap regression analysis was consistent with the hypothesis that PS partially mediated the effect of head injury on WM.

As expected, the TBI group performed below the combined comparison group on most of the PS and WM measures employed. Coding was significantly reduced following TBI, supporting previous findings that Coding effectively discriminates between head-injured and comparison children (Donders, & Janke, 2008; Ewing-Cobbs et al., 2008; Wozniak et al., 2007). The "gold standard" Coding task is multi-determined, with components of motor speed, visual motor coordination, and visual scanning. Given the complexity of the Coding task, it is probable that children who have sustained TBI are impacted by the perceptual and motor requirements of the task (Anderson & Fenwick, 1998; Catroppa & Anderson, 1999).

Relative to the combined comparison group, children with TBI correctly maintained and manipulated fewer visual-spatial sequences. Both the TBI and healthy comparison groups maintained and manipulated fewer words in verbal WM than the orthopedic group. This finding is consistent with prior studies indicating reduced verbal WM capacity (Conklin et al., 2008; Ewing Cobbs et al., 2004; Levin et al., 2002; Levin et al., 2004; Mandalis, Kinsella, Ong, & Anderson, 2007; Newsome et al., 2007; Roncadin et al., 2004; Serino et al., 2006) but also suggests the need to further understand verbal WM differences relative to both orthopedic and healthy comparison groups. The present study is unique in that it utilized two measures of WM with parallel processing requirements in verbal and visual-spatial modalities. Furthermore, because both WM tasks had the same processing demands and were on the same scale, it was possible to see whether WM performance for each group differed depending on the modality (verbal or visual-spatial) of presentation. Results suggested that the children with TBI and the children in each comparison group demonstrated a similar pattern of performance on verbal and visual-spatial WM tasks (also see Gorman et al., 2012) although the verbal WM differences were significant only compared to the orthopedic group. The pattern of scores was similar even though there was a significant difference in the range of general cognitive ability across the groups.

The influence of injury severity on outcomes changes over the course of recovery. Although severity of TBI has a robust effect on a host of outcomes during the first year after injury, other variables may play a central role during more chronic stages of recovery. In our sample, participants were on average 4 years post-TBI. Children with complicated-mild/moderate TBI had better Coding scores than children with severe TBI; however, severity groups did not differ significantly on either WM score. Despite the wide range in age at injury and time since injury, these variables were generally not significantly related to either the PS or verbal WM measures, when controlling for age at test. In contrast, lower visual-spatial WM scores tended to be associated with younger age at injury and were significantly associated with longer time since injury. The basis for the different findings relating developmental variables to verbal and visual-spatial WM is unclear. Visual-spatial WM may be more vulnerable than verbal WM in younger children following TBI due to differences in specific pathways supporting WM. For example, in a tractography study of callosal fibers, Treble et al. (2013) found that performance on both verbal and visual-spatial WM tasks was related to fibers from anterior and posterior parietal lobes and that visual-spatial WM was also related to temporal lobe fibers coursing through the posterior corpus callosum.

Our findings are similar to Anderson, Godfrey, Rosenfeld, and Catroppa (2012), who found residual severity group differences in PS, but few performance differences in other outcomes in children with mild, moderate, and severe TBI who were examined 10 years after injury. In their sample, outcomes were significantly related to preinjury level of functioning and the family environment, but not significantly related to injury variables, such as the depth of unconsciousness or white matter volume. Clearly, the influence of factors such as cognitive reserve, which includes preinjury child and family functioning, and time since injury play a crucial role in characterizing outcomes (Dennis, Yeates, Taylor, & Fletcher, 2006). With regard to time since injury, it has been previously found that greater time since injury is related to greater impairment in WM according to parent report, but not on direct assessment measures such as Digit Span Backward (Conklin et al., 2008). Our findings suggested that only visual-spatial WM was related to time since injury and also suggested that greater time since injury was related to poorer performance. Additional longitudinal studies are needed to track the trajectory of developmental changes in different areas of WM (and other cognitive domains) to identify areas of particular vulnerability or recovery after TBI.

Simulation analyses revealed that the relation between the Coding measure of PS and WM was similar for both the verbal and visual-spatial modalities. In the context of the Baddeley model of WM, the relation between PS and the phonological loop was the same as the relation between PS and the visuospatial sketchpad. Previous studies identified a relation between PS and verbal WM (Baddeley, 1981; Baddeley, 1986; Hulme et al., 1984; Kail, & Park, 1994). Chuah and Mayberry (1999) extended this finding and reported a relation between PS and both verbal and spatial WM. However, no previous study attempted to determine whether this relation was the same for both modalities. This is the first study to support the idea that the relation between PS and the phonological loop, and PS and the visuospatial sketchpad are similar. However, one must consider whether this is because the relation between PS and the phonological loop and PS and the visuospatial sketchpad are similar, or if it is because the phonological loop and visuospatial sketchpad are both strongly related to the central executive (Gathercole et al., 2004). This study did not attempt to partial out any shared variance between the two WM measures that could be related to the central executive so one must keep in mind that the relation between the two WM modalities may have been similar because of the relation between PS and the central executive.

Perhaps the most important and novel finding of this study was that bootstrap regression analysis was consistent with the notion that PS partially mediated the relation between head injury and WM, as compared to both orthopedic and healthy comparison children. While this mediating relation had been previously suggested by Fry and Hale (1996), this is the first study that provided evidence of the mediating effect in a pediatric TBI sample. Furthermore, this finding lends support to the idea that complex memory span is related to faster rates of rehearsal which allow for storage of a larger amount of information (Baddeley, 1981; Baddeley, 1986; Case et al., 1982; Hitch, Towse, & Hutton, 2001; Towse,

& Hitch, 1995; Towse, Hitch, & Hutton, 1998; Unsworth, Redick, Heitz, Broadway, & Engle, 2009).

Processing speed and WM are fundamental and intertwined abilities. Theories of cognitive development propose a cascade in which developmental increases in PS in turn lead to increases in WM, which then are associated with improvement in other cognitive abilities, including fluid reasoning (Fry & Hale, 1996; Kail & Salthouse, 1994) and academic skills (Christopher et al., 2012). Conversely, after TBI, changes in PS and/or WM may initiate a negative cascade of events. Slowed PS and/or reduced WM span may reduce efficiency or level of performance in an array of cognitive, psychological health, and academic outcomes. For example, Barnes, Dennis, and Wilkinson (1999) found that children with TBI had slower word decoding speed relative to children with comparable levels of phonological decoding and word reading accuracy; moreover, the slowed word-level reading created a bottleneck that reduced both reading fluency and reading comprehension. In the area of mathematics, Raghubar, Barnes, Prasad, Johnson, and Ewing-Cobbs (2013) examined factors related to mathematical computation and word problem solving following pediatric TBI or orthopedic injury. Calculation and problem solving performance was not accounted for by either speed or accuracy of arithmetic fact retrieval or speed on paper-pencil tasks involving single digit math facts. Rather, WM fully mediated the relation between TBI and math outcomes. In relation to social cognition, Dennis, Agostino, Roncadin, and Levin (2009) found that WM mediated the effects of cognitive inhibition on theory of mind abilities in children with TBI. Taken together, these studies highlight the major impact of post-traumatic changes in core PS and/or WM abilities on diverse outcomes.

Are PS and WM malleable after pediatric TBI and are they appropriate targets of intervention? Recent reviews highlight mixed results following training of PS, WM, and/or attentional control in children and adults. Although studies vary considerably in terms of the specific intervention, intensity, population, and active versus passive nature of comparison group activities, many studies show short-term improvements in PS and/or WM that are often not associated with transfer or long-term maintenance (see reviews by Melby-Lervag & Hulme, 2013; Wass, Scerif, & Johnson, 2012). Despite these limitations, there is some evidence that intensive cognitive training of attentional control and/or WM has more widespread transfer of training effects in children than in older individuals (Wass et al., 2012). Recent intervention studies support the malleability of PS in some child populations. Mackey, Hill, Stone, and Bunge (2011) found that a PS intervention produced large positive effects in low SES children; however, the gains did not transfer to WM or to fluid reasoning. Similarly, improvements in children receiving fluid reasoning training led to increases in reasoning but not PS (Mackey et al., 2011). In the context of intervention targets for children with TBI, it would be important to identify if PS and WM can be significantly enhanced by training, to determine if changes in one area produce a reciprocal change in the other, and to characterize any positive cascades in related cognitive areas.

Limitations and Future Directions

There are some limitations to the conclusions that can be drawn from the present study in terms of sample characteristics and the measures of PS. When considering the finding that

PS partially mediates the effect of head injury on WM, one should bear in mind the current mediation analysis was performed using a cross-sectional sample, which has been shown to over or underestimate longitudinal effects (Maxwell & Cole, 2007). Although combining the two TBI cohorts yielded a relatively large sample size, there may have been differences in treatment or exposures across the cohorts that influence outcomes. Future studies may want to include samples with a more limited range of time since injury, and examine this sample longitudinally to see if the mediation effect is consistent over time using multiple waves of data that can be examined using models of growth. Additionally, given the discrepancy in size between the TBI severity groups (with more than half of the sample consisting of children with severe injuries) the current study may have limited generalizability to children with less severe injuries. Future studies may attempt to include more balanced injury severity groups. It may also be of interest to consider different populations of children with developmental, or other acquired injuries, as well as adult samples, to determine whether this finding is specific to traumatic brain injury, or whether it generalizes across populations.

Coding is a factorally complex measure of PS; therefore, it is unclear if there are specific subskills such as visual motor, visual perceptual, and/or working memory that contribute substantially to the mediation. Future studies should include a variety of measures, such as automatized naming and complex RT tasks, to create latent variables and determine whether the partial mediation effect found in this study extends to other PS measures.

The present finding has implications for the classroom instruction for children with TBI and accommodations provided under the Individuals with Disabilities Education Act (IDEA, 1997). Many classroom activities involve WM. In particular, reading comprehension, and some aspects of mathematics have been related to verbal WM (Christopher et al., 2012; Siegel, 1994; Swanson & Jerman, 2006; Swanson, Zheng, & Jerman, 2009) and math has been related to visual-spatial working memory (D'Amico, & Guarnera, 2005; Passolunghi, & Cornoldi, 2008; Raghubar, Barnes, & Hecht, 2010; Reukhala, 2001). If performance in these areas declines following TBI, one should consider not only that it may be due to WM impairments, but also whether the children are time-limited when completing these tasks. For instance, children with TBI may be at a particular disadvantage on tasks such as math fluency worksheets because they are not able to retrieve and write the calculations as quickly as their peers. Due to the adverse impact of slowed PS and reduced WM, students should receive extended time to complete assignments, as well as extended time on both in-class and nationally administered tests. Children with TBI may also require reduced length of assignments, have information divided into smaller units to enhance rehearsal, and may benefit from the use of assistive technologies to reduce the impact of slowed PS on WM processes.

Conclusions

The present study lends further support to the existing body of literature demonstrating the detrimental effects of TBI on PS and WM and further supports using Coding as a “gold standard” measure sensitive to the effects of TBI on PS. Consistent with our previous work, this study suggests that both verbal and visual-spatial domains are similarly affected by TBI but the current study also suggests that the relation between PS and these two domains of

WM is similar. Of primary significance is our finding that PS appears to partially underlie deficits in WM following TBI, which provides a basis for future research on intervention strategies for remediation of cognitive deficits following pediatric TBI.

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Table 1

Demographics of Traumatic Brain Injury and Comparison Groups

	TBI (n = 77)	Orthopedic Comparison (n = 30)	Healthy Comparison (n = 40)	Statistic (df)	Significance
Ethnicity (n)					
Caucasian	44	11	25	X^2(6, N =147) = 7.77	*p* = .26
African American	10	8	7		
Hispanic	17	8	4		
Other/Mixed	6	3	4		
Sex (n)					
Female	22	14	17	X^2(2, N =147) = 4.06	*p* = .13
Male	55	16	23		
Maternal Education (M, SD, Range)	13.09(4.82) 3.00-21.00	14.70(4.19) 3.00-21.00	16.50(3.53) 3.00-21.00	*F*(2, 144) = 8.11 Tukey HSD	*p* < .01
Years of Age at Test (M, SD, Range)	13.23(3.24) 6.58-18.92	12.48(2.82) 8.58-17.67	12.08(3.53) 6.58-18.67	*F*(2, 144) = 1.81	*p* = .17
IQ (M, SD, Range)	98.18(16.55) 57-138	108.13(13.51) 83-140	112.83(13.68) 83-140	*F* (2, 144) = 13.42	*p* < .01

Table 2

Injury-Related Variables for Participants with Traumatic Brain Injury

Injury-Related Variables	Mean (SD) Range
Years of Age at Injury	9.23 (4.31) 0.17-16.00
Years Since Injury	4.00 (2.97) 0.66-12.25
Lowest GCS Score (n)	
13-15	7
9-12	16
3-8	54
Days to Follow Commands	5.91 (9.37) 0-41

Table 3a

Least Squares Means and Root Mean Square Errors of Processing Speed and Working Memory Measures for Traumatic Brain Injury and Comparison Groups

	Group			
	TBI	**Orthopedic**	**Healthy**	**Effect Size**
	Mean (RMSE)	**Mean (RMSE)**	**Mean (RMSE)**	R^2
Coding[a] Total completed	45.39 (12.51)	52.62 (12.51)	53.86 (12.51)	.50
Verbal WM[a, b] Correct Trials	10.39 (3.86)	13.06 (3.86)	10.88 (3.86)	.33
Visual-Spatial WM[a] Correct Trials	11.45 (3.40)	14.04 (3.40)	13.50 (3.40)	.42

Table 3b

	Severity of TBI		
	Complicated Mild/Moderate	**Severe**	**Effect Size**
	Mean (RMSE)	**Mean (RMSE)**	R^2
Coding[c] Total completed	54.07 (14.59)	44.24 (14.59)	.42
Verbal WM Correct Trials	10.87 (3.92)	10.70 (3.92)	.38
Visual-Spatial WM Correct Trials	12.74 (3.39)	11.44 (3.39)	.47

Note: Significant group comparisons

[a]TBI < both comparison groups

[b]healthy and TBI < orthopedic

[c]severe TBI < complicated mild-moderate TBI.

Table 4

Contrasts and Confidence Intervals for Mediation Analyses Testing the Direct and Indirect Effects of Group on Working Memory

Working Memory Measure	Contrast	Direct Effect	Indirect Effect 99% Confidence Interval	
			Lower Limit	Upper Limit
Verbal				
	TBI vs. Orthopedic	1.99*	0.093	1.614
	TBI vs. Healthy	0.02	0.133	1.77
Visual-Spatial				
	TBI vs. Orthopedic	2.00**	0.105	1.529
	TBI vs. Healthy	1.70*	0.144	1.715

Note:

* $p < .05$

** $p < .01$.